Brayton Cycle Power Conversion Model for MW-Class Nuclear Electric Propulsion Mars Missions

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A Brayton cycle based power conversion system for a nuclear electric propulsion application was modeled in Simulink as part of NASA's space nuclear program in order to explore the impact of technology assumptions on the power conversion system performance and capabilities. The thermodynamic processes and algorithms within the model are documented, including a higher fidelity reactor model. Assumptions are chosen based on literature and subject matter expert review, and example results and capabilities of the model are shown. The effects of the turbine inlet and compressor inlet temperature on radiator area and thermal efficiency are discussed. For a He-Xe closed Brayton cycle, radiator areas as low as 650 m^2/MW_e are shown, with corresponding thermal efficiences at roughly 20% for the minimal radiator area solutions.

I. INTRODUCTION

Nuclear electric propulsion is a promising option for interplanetary spaceflight, including human missions to Mars. The Brayton thermodynamic cycle is a possible configuration for the power conversion subsystem of an NEP vehicle and has been explored as an option for efficient and mass effective power generation and is one focus of NASA's space nuclear program.[1] While many of the underlying technologies that can enable capable NEP vehicles are still under development, thermodynamics-based modeling can be used to explore the design and performance space of such an NEP power conversion system and display the impact of technology assumptions.

II. BRAYTON MODEL PURPOSE AND DESCRIPTION

The purpose of the power conversion model is to investigate the impact of technology parameters on the power conversion cycle performance, radiator area, and ultimately the power system specific mass. A NEP (nuclear electric propulsion) power conversion model with a Brayton cycle was created in Simulink in order to parametrically explore the power conversion design space in support of TMP (technology maturation plan) development. This model encompasses a closed Brayton cycle system with radiator and reactor, which converges on a steady state thermodynamic cycle solution given the model input parameters. A summary of the components and the fluid flow diagram is shown in Fig. 1, with power values shown for an example case. At the system level, the radiator area is the primary driver of the system mass as a function of the technology selection and temperatures, but other parameters like reactor temperature, turbine inlet temperature, and number of fluid loops can also affect system performance.

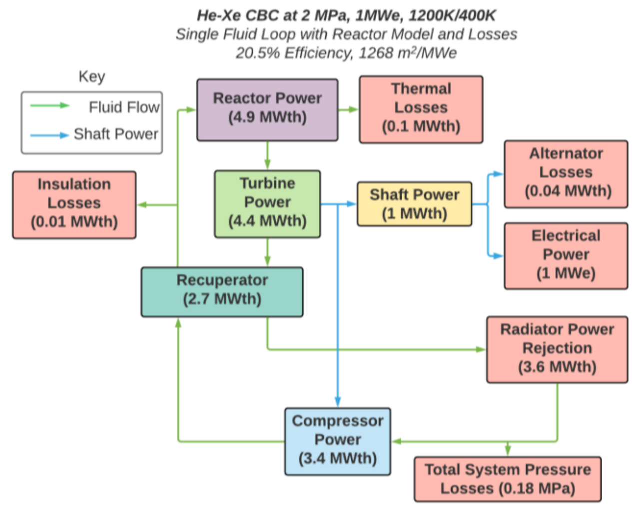

Fig. 1. Closed Brayton Cycle Layout and Flow Diagram

This model can utilize various Brayton cycle working fluids and multiple fluid loops if the reactor or radiator operates as a closed system with conditions or fluids that differ from the Brayton cycle. The current effort has focused on either a single fluid Brayton cycle, or a triple fluid Brayton cycle where the Brayton cycle operates with one fluid, and the radiator and reactor operate on other fluids with heat exchangers in between the fluid loops. The current model is an improvement on the work from Refs. 2 and 3 and was compared to work completed by Sandia[4] for reference and high-level verification. The output of the model directly feeds into a system mass model being developed concurrently.

The current primary areas of interest for the model are:

- Power cycle working fluid choices (primarily He-Xe, sCO_2)
- Advantages or disadvantages of separate reactor and radiator fluid loops
- Power cycle and reactor operating conditions

- Radiator outlet temperature and turbine pressure ratio optimization

II.A. Major Inputs and Outputs

The major model inputs and outputs are defined in Table I. The inputs are user or script provided values and are held constant throughout the modeling convergence process. The outputs vary until the convergence criteria of the model is reached, and then the output is saved. The outputs listed are the desired outputs for many of the analyses and inputs for the specific mass model.

TABLE I. Major Inputs and Outputs of the Brayton Cycle Model

Model Input	Model Output
Turbine Inlet Temperature	System States
Compressor Inlet Temperature	Component work
Desired Electrical Power	Radiator area
Turbomachinery Efficiencies	Thermal efficiency
Turbomachinery Pressure Ratio	
Heat exchanger effectiveness	
Radiator Properties	
Turbine Inlet Pressure	
Working fluid selection	
System thermal losses	

III. COMPONENT MODELS

The Brayton model consists of multiple component models that follow various thermodynamic processes. The equations listed in this section are for a fluid with near constant specific heat in the temperature range of each process, or if available thermodynamic properties are limited. A variant of these equations with enthalpy and entropy instead of specific heat is used for fluids such as supercritical CO_2 with highly variable specific heat. Variables used in this section that are not defined later in in the assumptions table are in Table II.

TABLE II. General variable descriptions

Description	Variable
Specific heat ratio	γ
Pressure ratio	PR
Temperature	T
Power	P
Specific heat	c_p
Heat transfer	Q
Heat capacity rate	C
Efficiency or effectiveness	η
Hot inlet	h, i
Cold outlet	c, o
Radiator calculation area step size	a_{step}
Mass flow rate	$\dot{m}$
Pump head	H_{pump}
Change in temperature	ΔT
Specific gravity	SG

III.A. Turbine and Compressor

For the turbine and compressor, the process is defined by a user defined pressure ratio and isentropic efficiency, using either specific heat or enthalpy and entropy depending on fluid properties.[5] For the turbine, the process starts by calculating an intermediate variable based on the pressure and specific heat ratio in Eq. (1). The outlet temperature of the fluid after changing pressure can be estimated with Eq. (2). After calculating the outlet pressure and temperature, the power generated is described in Eq. (3). The compressor utilizes similar equations.

$$c = PR_{Turbine}^{\frac{\gamma-1}{\gamma}} \tag{1}$$

$$T_{out} = T_{TIT} - T_{TIT} * \eta_{turbine} * \left(1 - \frac{1}{c}\right) \tag{2}$$

$$P_{generated} = \dot{m} * c_p * (T_{in} - T_{out}) \tag{3}$$

III.B. Recuperator

The recuperator is based on a nodal cross-flow heat exchanger model with total heat transfer determined by a NTU (number of transfer units) effectiveness.[6] A user-defined pressure drop as a percentage of inlet pressure can be used. As part of the NTU method, the maximum available heat transfer between the two fluids in the recuperator is defined in Eq. (4). Factoring in the effectiveness and inlet conditions, the outlet temperature of the hot side fluid is Eq. (5). The outlet temperature the cold side fluid would be similar, where the heat transfer is absorbed instead of lost.

$$Q_{max} = \left(\mathrm{T_{h,i}} - \mathrm{T_{c,i}}\right) * \min\left(C_h, C_c\right) \tag{4}$$

$$T_{h,o} = T_{h,i} - (Q_{max} * \eta_{recuperator})/C_h \tag{5}$$

If the chosen fluid has a highly variable specific heat, a specified outlet temperature difference between the two fluids can be used instead of specifying the recuperator effectiveness.

III.C. Reactor

The reactor model is based on an existing reactor thermal hydraulic sizing suite that allows for flexibility with working fluids and boundary conditions. Publication on the details and results for this model are in progress.[7] Key outcomes of this modeling approach as compared to a simpler approach is a higher fidelity pressure drop

calculation and thermal loss calculation. The model suite includes three major components:

1. Thermal hydraulics for core convergence
2. Monte Carlo neutronics (using the SERPENT tool) to assess the critical mass and power shape
3. Subcomponent mass constituents

The model imports a reactor inlet temperature, pressure, desired exit temperature, and total mass flow to predict the pressure drop, size, and total thermal power of the reactor. Radial dimensions and thermal power density values are varied in order to reach a desired reactor outlet temperature A breakdown of the modeling approach in the reactor model is seen in Fig. 2.

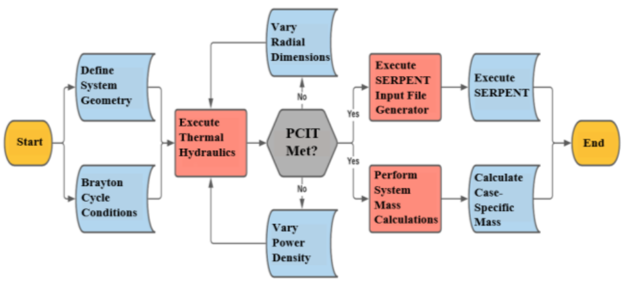

Fig. 2. Reactor modeling methodology

Two possible reactor configurations focused on are:

1. Direct gas cooled (e.g., sCO_2, He-Xe) reactor with a hex unit cell lattice design and internal cooling channels, connected directly to the Brayton system
2. Separate pumped liquid lithium reactor with pin-in-block configuration connected to a Brayton-reactor heat exchanger

The design trade space for the parametric NEP reactor model currently focuses on these configurations, but these may not represent the optimal choice for overall reactor performance or reactor mass. The direct gas cooled reactor configuration would be selected if the Brayton model consisted of a single fluid loop. Otherwise, the reactor would operate with the second configuration with a separate pumped loop and heat exchanger.

To simplify the power conversion system model and reduce computational time, thousands of test cases at various Brayton operating conditions (e.g., mass flow rate, temperature, pressure) have been simulated in advance. These data points are converted into a high fidelity, multi-dimensional spline fit lookup table. The Brayton model uses this lookup table during the cycle power balance convergence process. The list of input and output variables in the reactor spline fit functions are shown Table III.

TABLE III. Input/Output Variables in Reactor Spline Fit Functions

Input Variables	Output Variables
Reactor inlet pressure	Pressure drop
Reactor outlet temperature	Total thermal power
Reactor ΔT	Thermal power density
Total mass flow rate	Reactor mass

A subset of the spline fit data is shown as a surface plot in Fig. 3, with the color representing pressure drop as a function of reactor mass flow rate and inlet pressure for a He-Xe gas cooled reactor with an outlet temperature of 1200 K.

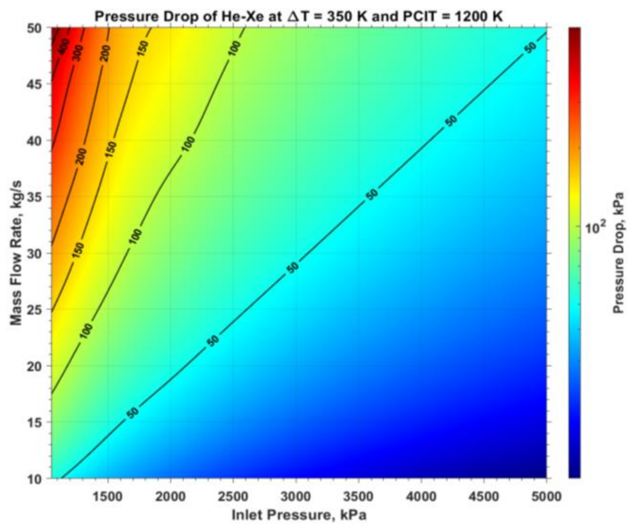

Fig. 3. Reactor model pressure drop as a function of inlet pressure and mass flow rate

III.D. Radiator

The radiator contains the process of heat transfer by radiation to a defined environment.[8] The major input of the radiator model is the desired outlet temperature of the fluid, and the major output is the required radiator area. The radiator is sized by iterating the radiator area by a specified area step size (a_{step}) until the fluid reaches the desired radiator outlet temperature. The specific heat loss to the environment at each step is shown in Eq. (6). The resulting temperature of the fluid after this heat loss is then defined in Eq. (7).

$$q_{step} = a_{step} F \varepsilon \sigma \left(T_{fluid}{}^4 - T_{sink}^4\right) \tag{6}$$

$$T_{out} = T_{in} - q_{step}/(\dot{m} * c_p) \tag{7}$$

III.E. Heat Exchanger

The heat exchanger model used between the Brayton loop and the other fluid loops (radiator and reactor) is

similar to the recuperator model, although the Brayton side outlet temperature is a specified value so the secondary side fluid inlet state must be solved iteratively. A summary of this process is:

1. Estimate initial secondary fluid inlet state based on user inputs, including the specified secondary loop maximum pressure

2. Calculate the required heat transfer to bring the Brayton fluid outlet to the specified temperature

3. Calculate the actual secondary fluid inlet state based on the NTU method and user inputs

4. Pass secondary fluid state and total heat transfer value to the reactor or radiator model

5. Compare model outlet state to actual secondary fluid inlet state from step 2, and iterate until error is within tolerance

III.F. Pumps

A pump model is used with the secondary fluid loops in order to calculate the pump work required to overcome pressure losses. Using a specified pump efficiency, outlet pressure, and fluid properties the pump work is calculated based on generalized pump equations with a constant specific heat.[9] This method was chosen as the fluid properties available for the selected fluids was limited. This pump is assumed to be powered electrically, and the electrical power is subtracted from the Brayton alternator power output. The temperature rise of the fluid as it undergoes the pressure increase is defined in Eq. (8). The power required to increase the fluid pressure is defined in Eq. (9). Details on these equations are found within the DOE Thermodynamics Handbook.[9]

$$\Delta T = H_{pump}(1-\eta_{pump})/(102 * c_p * \eta_{pump}) \tag{8}$$

$$P_{pump} = Q_{pump} * H_{pump} * SG/(367 * \eta_{pump}) \tag{9}$$

III.G. Alternator

Converting the mechanical work of the Brayton cycle into electrical work is assumed to be achieved with an alternator with a constant efficiency. The electrical power generated by the generator is defined in Eq. (10).

$$P_{electrical} = P_{shaft} * \eta_{alternator} \tag{10}$$

IV. BRAYTON CYCLE MODEL CONVERGENCE

The general algorithm for the model convergence and data collection process is:

1. Initial conditions and inputs are used to set model states, including the turbine pressure ratio

2. Calculate inlet and outlet conditions of each component, including the reactor model condition, and update model states

3. Calculate required Brayton cycle mass flow rate to achieve electrical power requirement after subtracting pump power usage

4. Compare the reactor outlet pressure or outlet pressure of the Brayton-reactor heat exchanger to the specified turbine inlet pressure, adjust compressor pressure ratio and reiterate until convergence criteria is met

5. Sweep a range of turbine pressure ratios (repeating 2-4) to optimize a model output, such as minimum radiator area

V. MODELING ASSUMPTIONS

Due to the accessibility and layout of the model, a wide range of fluids, components, and inputs can be used. The Brayton cycle model is agnostic to the fluid choice, provided that the appropriate thermodynamic properties of that fluid are available. The model uses an external function to call and retrieve property information throughout the cycle, which allows for easy modification as needed. The open-source library CoolProp[10] is used for the source of fluid properties. Based on current literature [11] – [16] and feedback from subject matter experts,[17] a list of assumptions was chosen, described as RB (Realistic Best) and listed in Table IV.

TABLE IV. Closed Brayton Cycle Assumptions

Model Parameter	He-Xe	CO_2
Max Turbine Inlet Temperature (T_{TIT})	1400 K	973 K
Turbine Inlet Pressure	2 MPa	20 MPa
He-Xe Ratio	0.72	N/A
Turbine Efficiency ($\eta_{turbine}$)	0.89	0.87
Compressor Efficiency ($\eta_{Compressor}$)	0.85	0.8
Radiator Emissivity ($\boldsymbol{\varepsilon}$)	0.9	0.9
Radiator View Factor (F)	0.85	0.85
Radiator Sink Temperature (T_{sink})	4 K	4 K
Recuperator Effectiveness ($\eta_{Recuperator}$)	0.9	0.9
Reactor Thermal Losses	2%	2%
Piping Thermal Losses	1%	1%
Alternator Efficiency ($\eta_{Alternator}$)	0.96	0.96
Reactor Pressure Drop	Model based	Model based
Radiator Pressure Drop	4%	4%
Recuperator Pressure Drop	3%	3%

Additional assumptions are made for Brayton cycle configurations with additional reactor or radiator fluid loops and are listed in Table V. The reactor fluid loop is assumed to use liquid lithium as the working fluid, and the radiator is assumed to use NaK-78 based on current literature.[1]

TABLE V. Closed Brayton Cycle Secondary Loop Assumptions

Fluid loop	Max Loop Pressure (kPa)	Component Pressure Loss (%)	Heat Exchanger Effectiveness	Heat Exchanger ΔP (%)	Pump Efficiency (η_{Pump})
Reactor loop with Lithium-7	2000	Model based	0.9	2%	0.19
Radiator loop with NaK-78	200	10%	0.9	2%	0.44

VI. MODELING EXAMPLE RESULTS

Two important metrics for a closed Brayton cycle power conversion system for an NEP application are:

- The thermal efficiency of the cycle, defined as the ratio of the net electrical power output to the reactor thermal output
- Radiator area required to close the thermodynamic system

As specific technologies haven't been selected for this model, the two metrics can be investigated as a function of the compressor inlet temperature and turbine inlet temperature. Using the model to produce individual data points across a variety of inputs results in Fig. 4. This plot shows the effect of turbine inlet and compressor inlet temperatures on the system radiator area and thermal efficiency. The contour lines indicate the thermal efficiency, and the color corresponds to the radiator area for an example cycle with the Realistic Best Assumptions case. The turbine pressure ratio is a user defined input, and each data point in the figure represents the turbine pressure ratio that results in the minimum radiator area. Only the results of the He-Xe gas-cooled model are presented for the sake of brevity.

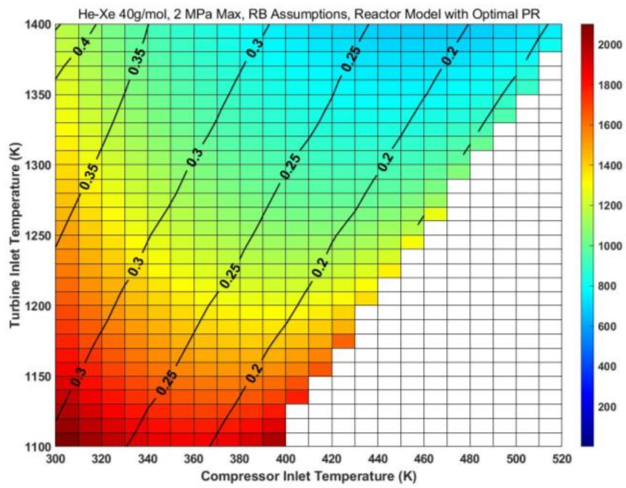

Fig. 4. Radiator area and thermal efficiency of a He-Xe closed Brayton cycle

A closer look at two specific turbine inlet temperatures, 1200 K and 1400 K, shown in Fig. 5, shows a clear trend where a specific compressor inlet temperature results in the minimum radiator area for a given turbine inlet temperature. The turbine inlet temperature has a strong impact on radiator area as well, in this example an increase in turbine inlet temperature by 200 K decreases the minimum radiator area by almost 50%.

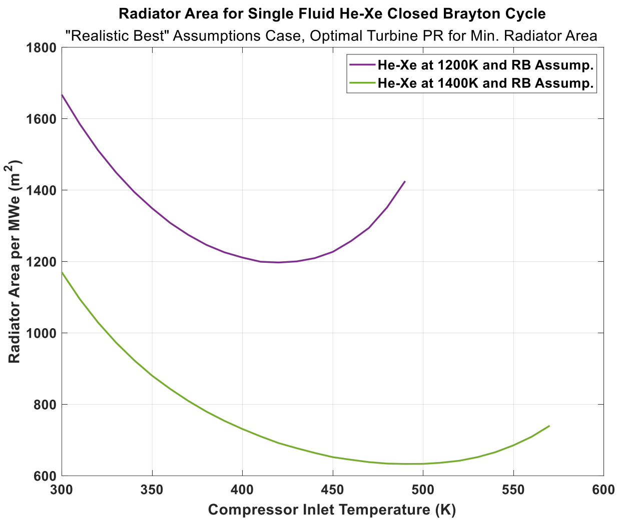

Fig. 5. Radiator area for two turbine inlet temperatures

General trends from these figures can be summarized as:

- Higher turbine inlet temperature enables a smaller radiator by:
  - Increasing average radiator temperature
  - Increasing thermal efficiency
- There is a compressor inlet temperature that results in the minimum radiator area for a given turbine inlet temperature
- Minimum radiator area occurs at a compressor inlet temperature well below the point of maximum thermal efficiency

Further sensitivity analyses can be performed with the model to determine the partial derivative of an input with an important metric like radiator area or efficiency. Shown in Fig. 6 is the difference in radiator area and cycle thermal efficiency between a turbine with an isentropic efficiency of 0.8 and 0.95 for a range of compressor inlet temperatures. The radiator area difference grows exponentially as the compressor inlet temperature increases past 340 K. Interpreted another way, increasing the turbine efficiency has an increasingly beneficial impact as the compressor inlet temperature increases past 340 K. In a similar fashion, the difference in cycle thermal efficiency increases as the compressor inlet temperature increases past 340 K. An important observation can be made by looking at Fig. 5, where the compressor inlet temperature of minimum radiator area is at approximately 420 K, which also coincides with the region in Fig. 6 where the cycle has a high sensitivity to turbine isentropic efficiency. This may suggest that operating the cycle off-optimal could allow for a more stable system.

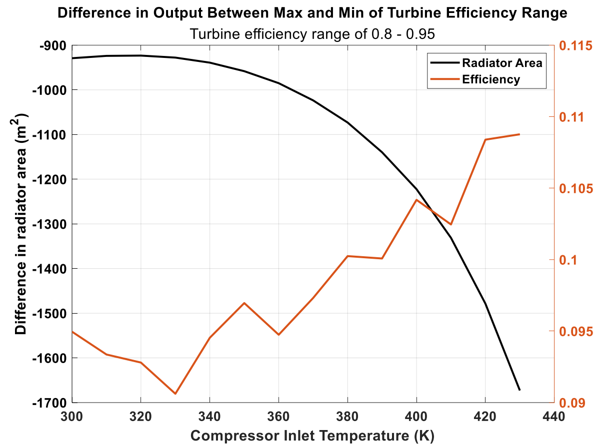

Fig. 6. Impact of turbine efficiency on radiator area and thermal efficiency

VII. FUTURE WORK

Continued development and improvements towards the model are planned in the near future, which would provide increased fidelity, validation, and additional sensitivity analyses. These tasks include:

- Integrating the radiator mass model into the Brayton cycle model, allowing for system wide radiator mass optimization
- Physics based recuperator and heat exchanger model which can calculate pressure losses, effectiveness, and mass as an output instead of an estimated user input
- Continue developing sensitivity analyses that can lead to additional conclusions and component specific performance suggestions
- Additional validation of model components

VIII. CONCLUSIONS

This paper describes a closed Brayton cycle model with a focus on a nuclear electrical propulsion application. After selecting an appropriate set of assumptions based on literature and subject matter expert feedback, example results are shown which indicate how the radiator area and cycle thermal efficiency are affected by cycle temperatures and model inputs, such as compressor inlet temperature. This model will continue to be improved and used in further work to develop additional results and conclusions that are aimed at providing suggestions towards future technology development and funding efforts for a NEP vehicle.

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